The age of the oldest globular clusters

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ABSTRACT

The age of three of the oldest clusters – M15, M68, M92 – has been redetermined. We use the latest EOS and opacity data available for calculating both isochrones and zero age horizontal branches and employ the brightness difference between turn-off and horizontal branch to determine the cluster age. Our best ages for all three clusters are about 13 Gyr, and even smaller ages are possible. Our results help to reconcile cluster ages with recent results on the age of the universe determined from the Hubble constant.

Subject headings: Galaxy: globular clusters: ages — globular clusters: individual (M15, M68, M92) — cosmology: universe, age — stars: low-mass, evolution

1. Introduction

If the age of the universe is obtained from the cosmological expansion by determining the Hubble constant H_0, it turns out to be less than 15 Gyr for $H_0 \gtrsim 50$km/(s Mpc) for values of the density parameter $\Omega_0 \gtrsim 0.4$. The most recent investigations into H_0 (for a review, see van den Bergh 1994) yield values between 60 and 90, which limit the age of the universe to less than 13 Gyr for any reasonable Ω_0, even if a cosmological constant is allowed. This number even reduces to 10 Gyr, if $H_0 \approx 75$ (from Cepheids or SNIa). Clearly, even if one stretches the limits, the universe appears to be younger than ≈ 15 Gyr.

On the other hand, the classical method of determining the age of the oldest known stellar objects, the isochrone fitting to metal-poor globular clusters, consistently yields ages above ≈ 14 Gyr for the bulk of metal-poor halo clusters, with the majority of the clusters being around 16 Gyr and the oldest ones up to 18 Gyr old. An additional Gyr has to be added to this for the time between the genesis of the universe and the creation of the first clusters. This "Conflict over the age of the Universe" has been brought to the point by Bolte & Hogan (1995) by the example of M92, probably the best observed very old cluster, whose age they give as 15.8 ± 2.1 Gyr (this range was used by Kennicutt, Freedman & Mould (1995) to illustrate the relation – and conflict – with H_0).

It therefore is necessary to reconsider age determinations of globular clusters and to investigate the errors more carefully. In this *Letter* we report about new age determinations of three of the oldest clusters, including M92, using standard approaches, but latest equation of state and opacities for the stellar models. Cluster ages were determined by using the difference in visual magnitude ($\Delta(V)$) between main-sequence turn-off and horizontal branch (HB).

Our work is similar to Chaboyer & Kim (1995; CK95), who used the same method and already found a reduction of cluster ages of about 7% (or 1.2 Gyr for the oldest clusters). However, they had determined $\Delta(V)$ from the difference between the theoretical turn-off luminosity V_{TO} and an empirical horizontal branch brightness V_{HB} (based on RR Lyrae luminosities). In contrast, we calculate theoretical ZAHBs

as well and fit both isochrones and ZAHB to the observations. This way, the influence of the new input physics is taken into account twice.

In the next section we will shortly describe our model calculations; Sect. 3 contains the comparison with the globular clusters M15, M68 and M92. We have concentrated on these three very old clusters, because the intention of this *Letter* is to reconcile cluster and cosmological ages. In a forthcoming paper we will discuss a larger set of clusters in a broader context. The conclusions will follow in the last section, as usual.

2. Models

All the evolutionary calculations presented in the paper have been performed with the Frascati Raphson Newton Evolutionary Code (FRANEC) whose general features and physical inputs have already been described in previous papers (see e.g. Chieffi & Straniero 1989). We have adopted the OPAL opacity tables (Rogers & Iglesias 1992; Rogers & Iglesias 1995; Iglesias & Rogers 1995; Rogers 1995, private communication) combined with the molecular opacities by Alexander & Ferguson (1994). More precisely, two sets of opacity tables (Alexander, Iglesias and Rogers, private communication) were used, one for a scaled solar metal mixture (Grevesse & Noels 1993) and one for the same heavy element fraction Z, but with the α-elements being enhanced relative to the iron within the metal group. In particular, oxygen is enhanced by $[O/Fe] = 0.5$, and the other α-elements by similar, but slightly varying amounts, according to the observed values in low metallicity stars (see e.g. Wheeler et al. 1989). It should be emphasized that the metal mixtures for both the low (molecular)- and high-temperature opacity tables are exactly the same. Thus we were able to compare consistently stellar models with the same total metallicity but with different internal distributions of the heavy elements. In the high density region, which is not covered by the OPAL opacities and in which the dominant source of opacity is due to the electron conduction, we used the opacity coefficients by Itoh et al. (1983).

As for the equation of state (EOS), the updated OPAL EOS (Rogers 1994; Rogers, Swenson & Iglesias 1996) has been used, upon which the OPAL opacities also rest. In regions, where the OPAL EOS is not available, we supplemented it by the EOS described by Chieffi & Straniero (1989; for $T < 5000$ K) and Straniero (1988; for degenerate He cores and the central regions of non-degenerate ZAHB He cores). We have verified that the transition from the OPAL to the supplementary EOS is smooth and without discontinuities.

Stellar models were evolved with a total metallicity of Z=0.0002 and Z=0.0004, a scaled solar and an α-enhanced metal distribution, and helium abundances Y=0.23 and Y=0.24. These mixtures were chosen to match the observed values. For each given chemical composition, models with masses ranging from 0.7 to 1 $M_\odot$ were evolved from the Zero Age Main Sequence (ZAMS) up to the Red Giant Branch (RGB) until a luminosity of Log $L/L_\odot \approx 1.7$. We have chosen 0.7 $M_\odot$ as a lower mass limit for our models in order to have, at least for the evolution up to the turn-off point (TO), all the structure of our models covered by the OPAL EOS (see also the discussion in CK95). In all models a mixing length of 1.6 was used; we checked that with this value of the mixing length the observational data of Frogel et al. (1983) for the temperatures of the RGB are reproduced. Isochrones were constructed by interpolating among evolutionary tracks for each selected chemical composition.

The 0.8 $M_\odot$ models have been evolved until the core helium flash to derive the mass of the helium core and the envelope He abundance after the first dredge-up; for this mass the stellar age at the He–flash

is of the order of 13 Gyr, roughly representative of our derived age for metal-poor globular clusters (see the following section). For the ZAHB models, we employed the He core mass and the envelope chemical composition at the flash and computed an initial set of He-burning models with different masses of the H-rich envelopes. Following Castellani et al. (1991), we assumed as ZAHB structures models already evolved by 1 Myr, which should represent quite accurately the theoretical counterparts of the lower luminosity boundaries of the observed HBs.

The color transformations and bolometric corrections used to transform theoretical temperatures and luminosities into magnitudes in the UBV system came from Buser & Kurucz (1978, 1992, hereinafter BK78, BK92). We adopted the BK92 transformations for $T \leq 6000$ K, and the BK78 at higher temperatures according to the suggestions by BK92. For each metallicity, the two sets have two temperatures in common (5500 and 6000 K, resp.), and we have shifted the $B-V$ values by BK78 in order to match the corresponding ones by BK92 at these two temperatures (see also De Santis 1996). This set of transformations, as discussed by BK92, is highly homogeneus, and covers all the evolutionary stages displayed in the Color Magnitude Diagrams of the studied clusters.

As a comment, we add that we confirm a result obtained by Salaris, Chieffi & Straniero (1993): Comparing the α-enhanced isochrones and ZAHBs with the scaled solar ones for the same total metallicity, we find that the α-enhanced models are well reproduced by scaled solar ones . In contrast to Salaris et al. (1993) we had access to opacity tables reflecting the α-enhancement for all temperatures. Note that this equivalence holds for low metallicities only (Weiss, Peletier & Matteucci 1994)

3. Cluster fits

The α-enhanced isochrones described in the previous section have been used for determining the ages of metal poor galactic globular clusters. We have selected M92 (NGC6341), M68 (NGC4590) and M15 (NGC7078) as being representative of the old metal-poor globular cluster population. These three clusters have been extensively studied in the past, and according to various authors (see e.g. Vandenberg, Bolte & Stetson 1990; Straniero & Chieffi 1991; Chaboyer, Sarajedini & Demarque 1992; Salaris et al. 1993) they are among the oldest clusters in the Galaxy; therefore their age put strong constraints on the age of the universe and on the Hubble constant. The ages derived in the past years, adopting different theoretical isochrones and different age indicators (as the $\Delta(V)$ and the $\Delta(B-V)$, see the discussion in Salaris et al. 1993), range between 15 and 20 Gyr for M15 and M92, and between 13 and 19 Gyr for M68 (see e.g. Straniero & Chieffi 1991; Carney et al. 1992; Chaboyer et al. 1992). Very recently, by using the OPAL equation of state in computing the theoretical evolutionary models, Mazzitelli, D'Antona & Caloi (1995) found an age of around 14 Gyr for M68, while CK95 obtained 17, 15 and 13 Gyr for M92, M15 and M68, respectively. All these authors use the $\Delta(V)$ age indicator in order to derive the age of the clusters. In our analysis we have adopted the recent photometry by Carney et al. (1994) together with the fiducial line from the work by Stetson & Harris (1987) for the cluster M92; in the case of M68 and M15 we have used the data published by Walker (1994) and by Hasley & Christian (1994), respectively. The values of $[M/H]$ (taking into account the observed overabundance of the α-elements) adopted for the clusters come from the paper by Salaris & Cassisi (1996), where spectroscopical determinations of $[\alpha/Fe]$ and $[Fe/H]$ are collected for a sample of 22 globular clusters.

In Figs. 1, 2 and 3 the fit of the theoretical isochrones to the observational data of the three clusters is displayed. On the data by Carney et al. (1992) for M92 the main line by Stetson & Harris (1988) for the

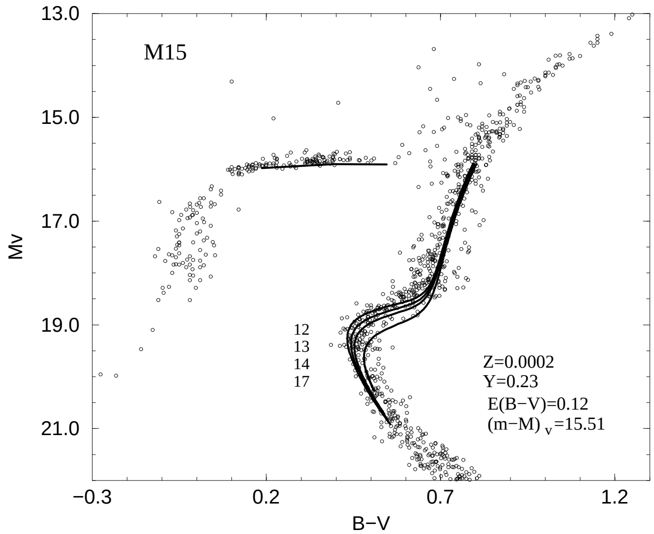

Fig. 1.— Isochrones for different ages (given in Gyrs in the figure) fitted to the CMD of M15. Composition, reddening and distance modulus are displayed in the lower right corner. For comparison, an isochrone of 17 Gyr is shown as well. See text for more details.

MS and RGB loci has been superposed, while in the case of M68, for a sake of clarity, we have displayed the photometry from only two fields among the long exposure frames, and the data from all the short exposure frames. We have derived the distance moduli of the clusters and their reddening by simultaneously superposing our ZAHB location to the lower envelope of the observed horizontal part of the clusters HBs in the region of the RR-Lyrae stars, and by fitting with the isochrones the observed MS and RGB loci. Once distance modulus and reddening are fixed, the fit to the TO luminosity provides the age of the cluster. By adopting Y=0.23 and a metallicity Z=0.0002 for M92 and M15 (corresponding approximatively to the estimated values [M/H]=-2.04 and -2.09) we derived from the fit an age of 13–14 Gyr for M92, 12–13 Gyr for M15. In the case of M68 the estimated value of [M/H]=-1.78 corresponds approximatively to a metallicity Z=0.0004. The derived age is 12–13 Gyr, too. Note that our ages are again lower as compared to CK95. For the same cluster, we have tested the influence of a slightly higher original helium content (Y=0.24) and of a variation of the metallicity by a factor of 2 (Z=0.0002). In the first case we obtained a reduction of the age by slightly less then 1 Gyr, in the latter case an increase by the same amount; both findings are in agreement with Salaris et al. (1994).

We have also derived the age of M68 using the α-enhanced isochrones transformed to the observational plane by adopting the transformations by Kurucz (1992). These transformations cover homogeneously all the range of effective temperatures and gravities from the MS to the HB evolutionary phase. Since there is some concern about the Kurucz (B-V)-Teff relation, especially for RGB metal poor stars (see e.g. Bell et al. 1994; McQuitty et al 1994; Gratton et al. 1996; D'Antona & Mazzitelli 1996; Alexander et al. 1996), we have only considered the difference in luminosity between the observational ZAHB in the region of the RR-Lyrae stars and the TO of the cluster, obtaining an age reduced by almost 1 Gyr with respect to the fit displayed in Fig. 2.

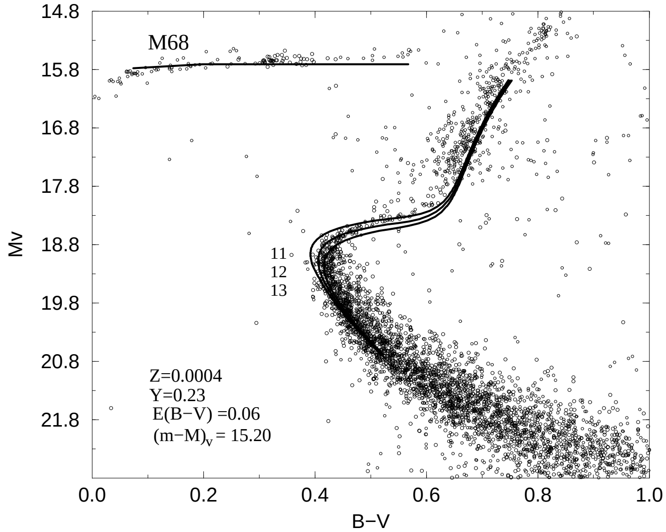

Fig. 2.— Same as Fig. 1, but for M68.

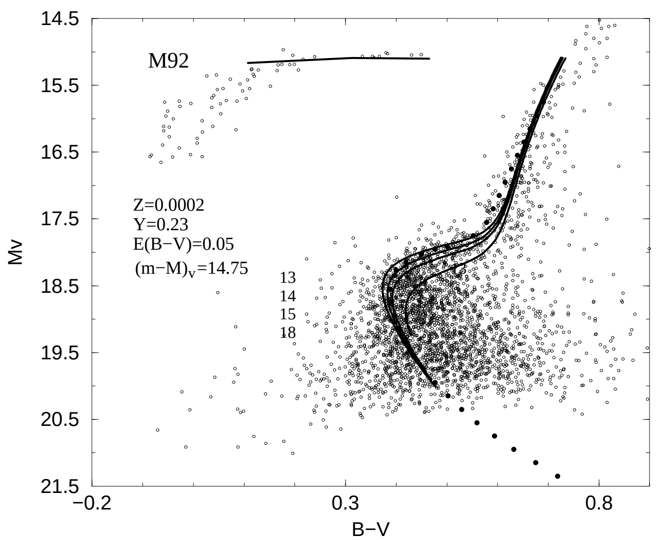

Fig. 3.— Same as Fig. 1, but for M92. The filled dots are the fiducial line of Stetson & Harris 1988. For comparison, an isochrone for 18 Gyr (the preferred age of M92 in the past) is shown.

4. Discussion and conclusions

In this paper we have reexamined the age of three of the oldest globular clusters (M15, M68, M92). Changes to earlier work included the use of the latest OPAL EOS and opacity tables, supplemented by low-temperature opacity tables for *exactly* the same compositions. In particular, α-enhancement within the metals could be taken into account. For appropriate chemical compositions both isochrones *and* ZAHB models were calculated and cluster ages were derived from the $\Delta(V)$ difference between TO and ZAHB. We find that the age of the clusters is about 13 Gyr, and that the three clusters are practically coeval. These ages are lower by up to 4–5 Gyr as compared to earlier results, e.g. Salaris et al. (1993). They made use of the bolometric corrections of Vandenberg & Bell (1985) for the TO, while we switched to BK92 and BK78. This, as we have checked, lowers the ages already by almost 2 Gyrs. The additional age reduction results from the new OPAL EOS. Our results confirm and extend those of CK95 and Mazzitelli et al. (1995). The further reduction as compared to CK95 is due to our additional ZAHB calculations.

The derived ages *can further be reduced* by the following means: a) the use of a higher helium content, justified by Big Bang Nucleosynthesis results on the best-fit predicted primordial helium content of 0.247 (Hata et al. 1996) or by observations including a large systematic error (Olive & Steigman 1995); b) the use of the new Kurucz (1992) bolometric corrections; we did not use them because of the problems encountered with RGB colors; c) the inclusion of diffusion (Chaboyer et al. 1992). Each of these factors reduces the ages by another 0.5 Gyr at least, such that an age of the oldest globular clusters of 12 Gyr seems to be in reach.

Interestingly, the mean age obtained for the three clusters is almost coincident with the age of the Disk (10–12 Gyr) obtained by Hernanz et al. (1994) by means of the luminosity function of the white dwarfs in the solar neighbourood, thus implying that the Galactic Disk began to form without time delay with respect to the halo.

In a forthcoming paper we will present extended results for a large sample of clusters. The bottom line of the present *Letter* is that with updated physics the oldest globular clusters are only 13 Gyr (or less) old. This reduces the "Age Conflict" drastically. Stellar evolution theorists have done the first step. It is now for the cosmologists to confirm that $H_0 \approx 50$.

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